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LAND SUITABILITY ASSESSMENT FOR AFFORESTATION WITH *ELAEAGNUS ANGUSTIFOLIA* L. IN DEGRADED AGRICULTURAL AREAS OF THE LOWER AMUDARYA RIVER BASIN

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ABSTRACT

Degradation of irrigated croplands in arid regions is of great environmental concern worldwide. Based on a series of field trials, afforestation with well-adapted tree species was evaluated as a viable option for the cropland rehabilitation in the lower reaches of the Amudarya River basin in Uzbekistan. Our aim was to extend available site-specific information for the entire regional landscape and provide spatially explicit guidance in support of afforestation land rehabilitation efforts. To this end, a geographic information system—based multicriteria decision-making approach has been developed for assessing the suitability of degraded irrigated cropland for introducing plantations of *Elaeagnus angustifolia* L. This approach utilized expert knowledge, fuzzy logic, and a weighted linear combination to produce an afforestation land suitability map. Overall, 75 287 ha of degraded croplands (18% of the irrigated cropland area) was identified as suitable for introduction of *E. angustifolia*. We also conclude that irrigation water supply and groundwater table depth are the critical factors determining the suitability of degraded irrigated land. These findings improve an understanding of the spatial variability of areas suitable for the initiation of agroforests and support better informed decisions on cropland rehabilitation. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS: land evaluation; agroforestry; land degradation; multicriteria evaluation; fuzzy logic; GIS; Central Asia

INTRODUCTION

In Central Asia as well as in other irrigated regions in the world, the problem of cropland degradation as a result of soil salinity is acute, particularly in river valleys and downstream areas (Dubovyk *et al*., 2013a). A number of methods have been developed for rehabilitating degraded cropland. Afforestation with salt-tolerant tree species is a viable option (König *et al*., 2012; Rigueiro-Rodríguez *et al*., 2012), especially for areas characterized by shallow saline groundwater tables (GWTs). The lower Amudarya River basin of Uzbekistan is such an area. Published research has addressed several aspects of afforestation. Lamers *et al*. (2006), Khamzina (2006), and Khamzina *et al*. (2006) have evaluated the suitability of selected tree species for afforestation. Khamzina *et al*. (2008) examined the establishment, irrigation demands, and groundwater uses by tree plantations. Several researchers have focused on the potential for afforestation to replenish soil nutrient stocks and improve soil quality (Hbirkou *et al*., 2011; Fialho & Zinn, 2012; Bruun *et al*., in press; Vasconcellos *et al*., 2013; Wu *et al*., 2013). More recently, the feasibility of extending specific afforestation efforts to cropping sites removed from cultivation has been explored (Schachtsiek *et al*., 2014). Native tree species that have been evaluated include *Elaeagnus angustifolia* L., a multipurpose, N_2-fixing, salt-tolerant, and fast-growing species with a high potential for afforestation of nutrient-depleted sites affected by salinity.

These site-specific results must now be extended to determine the size, distribution, and overall area of degraded cropland parcels that are best suited for afforestation in irrigated agricultural landscapes. Land suitability for introducing forestry in degraded agricultural areas differs spatially because of variable landscape characteristics that determine tree survival and establishment. Thus, spatially explicit information is vital for effective allocation of land resources to create a basis for efficient environmental policy intervention.

Multicriteria decision making is a useful approach for land evaluation. This approach allows the analyst to combine qualitative and quantitative criteria in determining site-specific suitability values for a proposed land use option. Geographic information systems (GISs) are well suited for manipulating a wide range of data from various sources for cost-effective and time-efficient analyses (Pandey *et al*., 2011). A number of GIS-based multicriteria evaluation (MCE) methods have been tested in research applications (Malczewski, 2004; Jarnevich & Reynolds, 2011).

The focus of our study was to develop and apply a GIS-based MCE approach to assess the suitability of degraded irrigated cropland for conversion to tree plantations of *E. angustifolia* in the lower Amudarya River basin region of Uzbekistan. We also seek to contribute in a functional way to land rehabilitation efforts in the region.

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MATERIALS AND METHODS

Study Area

The study area included the Khorezm Province and the southern part of the Autonomous Republic of Karakalpakstan [Sertifikat Kelayakan Konstruksi Platform (SKKP); Figure 1c] located in the lower reaches of the Amudarya River in Uzbekistan (Figure 1a, b). The region covers an area of about 662 042 ha, of which 410 000 ha is arable irrigated land (Tüshaus *et al.*, 2014). The area is characterized by the extreme continental climate with an annual rainfall below 100 mm. The Amudarya River is the main source of fresh water for the irrigated agriculture production, which is the backbone of the regional economy (Conrad *et al.*, 2014).

Natural riparian and desert forests have been greatly reduced as the irrigated cropland expanded since the 1960s. Trees, mostly in the form of fruit orchards and windbreaks, occur on less than 2% of the agricultural area. Principal tree species include *Morus alba* L., hybrid *Populus* spp., *Salix* spp., and *E. angustifolia*.

The regional hydrology is characterized by a naturally shallow GWT level with a long-term average depth of 1·2 m and low to moderate salinity levels (1·8 g/l) that are affected by irrigation inputs (Ibrakhimov *et al.*, 2007). Because of rising GWT and resulting soil salinization, cropland degradation is an acute problem. Land productivity is declining in approximately 20% (94 835 ha) of the arable area (Dubovyk *et al.*, 2013a).

Data Sources

The data on the performance of *E. angustifolia* in the study area were derived from published reports and original datasets based on eight experimental afforestation sites in Khorezm and SKKP (Table I). All sites were treated with less than 200 mm of irrigation for the first 2 years and thereafter relied fully on groundwater.

Data on the suitability criteria were obtained from the ZEF/UNESCO project database (www.zef.de/) established through statistical data collection from various institutions. The obtained datasets were preprocessed and converted into the GIS format. All datasets were converted to the same coordinate system (European Datum 1950 Universal Transverse Mercator Zone 41N) with the same spatial extent and 250-m cell size. The cropland degradation trend map, calculated from the 250-m Moderate Resolution Imaging Spectroradiometer (MODIS) time series (2000–2010; Dubovyk *et al.*, 2013a), was used as the basis to define the suitability of degraded cropland for afforestation with *E. angustifolia*.

Multicriteria Evaluation

The development of a GIS-based MCE in the suitability analysis of degraded irrigated cropland for afforesting with *E. angustifolia* involved as follows: (i) identification of the factors determining survival and establishment rates of *E. angustifolia* saplings that served as land suitability criteria for afforestation; (ii) specification of the quantitative relationship between tree establishment and each selected criterion; (iii) definition of a range of suitability values for each

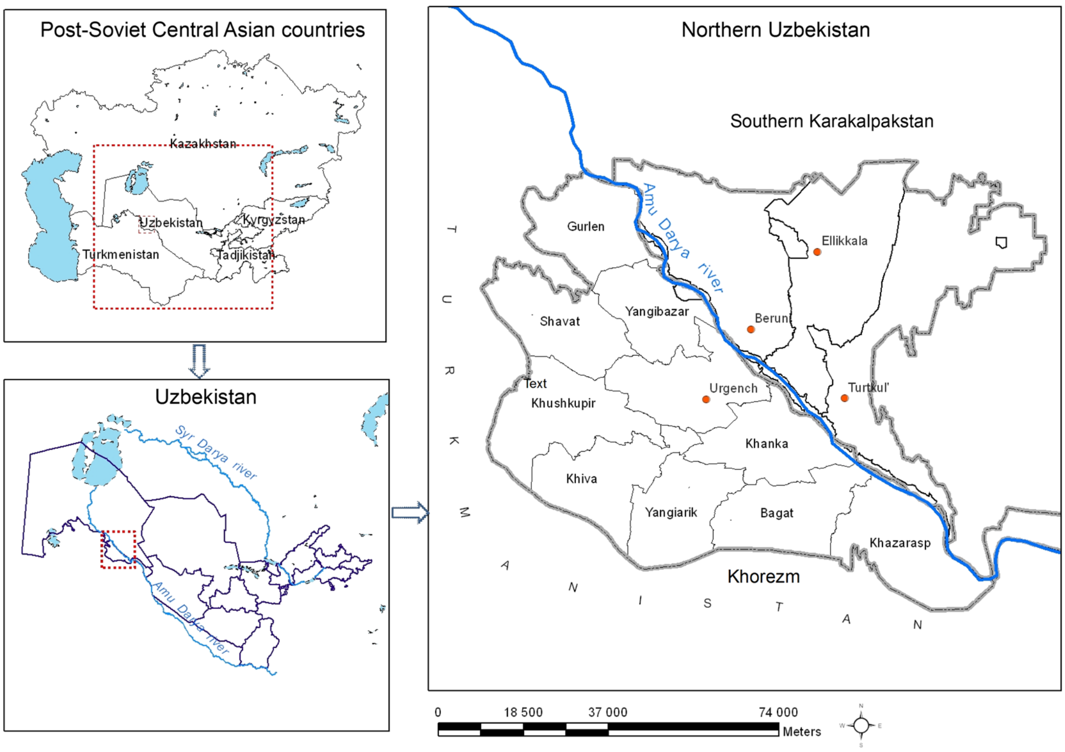

Figure 1. Location of the study area in the lower Amudarya River basin in Uzbekistan.

Table I. Suitability ranges of the groundwater conditions for the afforestation with *E. angustifolia*

Optimal range/range in experimental trials			
GWS, g/l	GWT, m	Ecosystem/Location	References
2·0–5·0	0·6–1·7	Afforestation on silt-loamy and sandy cropland soils in Khorezm	Khamzina (2006); Khamzina *et al.* (2006)
0·6–5·4	0·7–2·2	Afforestation on marginal cropping sites with silt-loam soils in Khorezm	Khamzina *et al.* (2008; 2009); Djumaeva *et al.* (2013)
1·4–4·2	0·4–2·2	Afforestation on abandoned cropping sites with silt-loamy and sandy soils in Khorezm and SKKP	Schachtsiek *et al.* (2014); Dubovyk *et al.* (2012)
—	1·5–3·0	Afforestation on sandy desert soil in Minqin oasis of northwest China	Kang *et al.* (2004)

criterion; and (iv) combination of the criteria to determine the overall suitability of land for tree planting.

The ordered weighted averaging (OWA) technique was selected for multicriteria aggregation of the weighted criteria (Yager, 1988). Previous research has shown that the combination of fuzzy logic (Zadeh, 1965) and OWA can yield promising results for land suitability analyses (Chen & Paydar, 2012). Weighted linear combination (WLC) is one of the most frequently used decision rules in GIS and is also a specific case of an OWA (Boroushaki & Malczewski, 2008); this procedure was adapted in this study.

In WLC, criterion weights indicate the relative importance of each criterion to the objective under consideration. In this study, simple ranking was applied to rate criteria from 1 (least important) to 5 (most important) based on expert knowledge.

General Environmental Requirements and Reclamation Characteristics of *E. angustifolia*

The N_2-fixing, deciduous tree species *E. angustifolia* L., native to Central and West Asia and southern Europe, is useful for fruit, fuel wood, gum, leaf fodder, nectar and honey production, medicinal purposes, and ornamental planting (Katz & Shafroth, 2003; Khamzina *et al*., 2009). It can withstand temperatures ranging from −45°C to 45°C and occur from sea level to above 2000-m elevation. While preferring sandy floodplains, *E. angustifolia* is often associated with moist riparian habitats but withstands droughts and is able to grow in a wide range of climatic and soil conditions. Particularly, because of its ability to pioneer disturbed sites, it has been widely propagated as a wildlife, windbreak, road hedgerow, and reclamation species. In riparian ecosystems, *E. angustifolia* can colonize aggressively, displacing native vegetation and might be regarded as an invasive exotic, for example, in the USA (Katz & Shafroth, 2003). However, the ability to fix atmospheric N allows *E. angustifolia* to colonize N-depleted soils, thus building up soil organic matter and creating suitable habitat for other plants. Mixing valuable tree crops with *E. angustifolia* was shown to improve their growth performance (Paschke, 1997).

Criteria Selection and Standardization

The list of criteria was based on the conclusions of afforestation experts involved in afforestation trials in the region. The list included local environmental factors favorable for *E. angustifolia* survival and defined their presence within the study landscape. The final selection of the criteria was guided by the GIS data availability.

To define a range of suitability values for each criterion, a literature review was performed, and interviews were conducted with local afforestation experts. This information was formalized using a fuzzy set approach. For each criterion, a suitability function was defined that assigned a degree of suitability to every value of the criterion. Subsequently, the criterion maps were recompiled in the GIS according to the selected fuzzy function. A fuzzy set is characterized by a fuzzy membership grade without sharp boundaries, with grade values ranging from 0 to 1. This scale indicates a continuous increase from nonsuitability ("nonmembership") to complete suitability ("membership") as described by Dubois and Prade (1982). Depending on the selected type of fuzzy set membership functions, the positions of a maximum of four points governs the shape of the fuzzy curve (Figure 2):

- a = membership rises above 0
- b = membership becomes 1
- c = membership falls below 1
- d = membership becomes 0.

Irrigation water supply

Parameters describing irrigation water availability and groundwater characteristics are of paramount importance in determining the land suitability for dryland afforestation. This is because of irrigation needs at the early stage of tree growth to counterbalance the salt stress and to satisfy the water demand before trees can rely on groundwater (Khamzina *et al*., 2008). To account for this condition, the regional irrigation water supplies showing differences for each pair of years between 2000 and 2010 were calculated for each agricultural district (Figure 1) and averaged over 11 years. Negative values indicate that the water supply has decreased for some districts over the last decade, whereas positive values indicate an increase. The district with the highest increase in water supply was considered as the most suitable for the establishment of tree plantations (suitability score = 1), whereas the district with the highest decrease in water supply was considered as the least suitable (suitability score = 0; Table II, Figure 2). Following discussion with experts, relationships for all criteria related to the irrigation water and irrigation network were assumed to be linear. A monotonically decreasing linear function was then

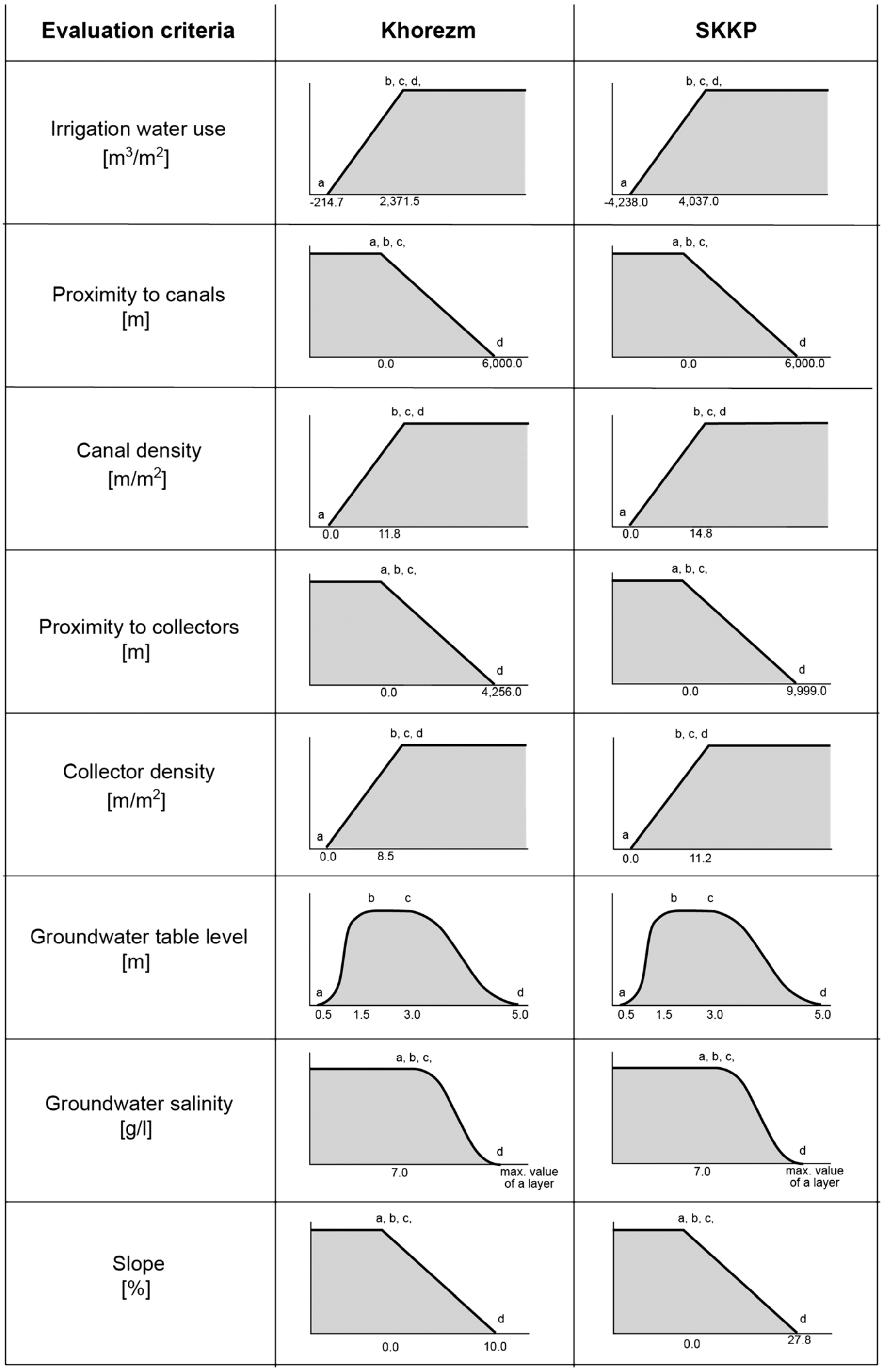

Figure 2. Fuzzy set membership functions used for the criterion map standardization in Table II.

implemented to rescale criterion of irrigation water supply, that is, sites with the lowest irrigation supply had the lowest suitability score, and sites with the largest supply had the highest suitability score. This function used minimum and maximum values from the irrigation water supply map as the control points at the end of the linear curve (Figure 2).

Irrigation network

As an access to irrigation water depends on the site location within the irrigation infrastructure, the criteria "proximity to irrigation canals" and "density of irrigation canals" were incorporated into the analysis.

The criterion "proximity to irrigation canal" was rescaled using the monotonically decreasing linear function (Figure 2). The areas closest to irrigation canals were considered most suitable (suitability score = 1) in contrast to least suitable remote areas (suitability score = 0; Table II, Figure 2). The criterion "density of irrigation canals" was rescaled using a monotonically increasing linear function. Areas with the highest canal density were considered most suitable

Table II. Evaluation criteria and fuzzy membership function parameters for land suitability modeling

Evaluation criteria	Type of fuzzy membership function	Inflation points of fuzzy membership function				Rank assigned by experts	Weight
		a	b	c	d		
Irrigation water use in Khorezm, m^3/m^2	Monotonically increasing linear	2371·53	−214·72	−214·72	−214·72	5	0·14
Irrigation water use in SKKP, m^3/m^2		−4238·0	4,037·0	4037·0	4037·0		0·15
Proximity to canals in Khorezm, m	Monotonically decreasing linear	0·0	0·0	0·0	6000·0	4	0·11
Proximity to canals in SKKP, m							0·12
Canal density in Khorezm, m/m^2	Monotonically increasing linear	0·0	11·78	11·78	11·78	4	0·11
Canal density in SKKP, m/m^2		0·0	14·76	14·76	14·76		0·12
Proximity to collectors in Khorezm, m	Monotonically decreasing linear	0·0	0·0	0·0	4256·30	2	0·06
Proximity to collectors in SKKP, m		0·0	0·0	0·0	9999·54		
Collector density in Khorezm, m/m^2	Monotonically increasing linear	0.0	8·45	8·45	8·45	2	0·06
Collector density in SKKP, m/m^2		0·0	11·15	11·15	11·15		
Groundwater table level in Khorezm[a], m	Symmetric sigmoidal	0·5	1·5	3·0	5·0	3	3 × 0·08
Groundwater table in SKKP[a], m							3 × 0·09
Groundwater salinity in Khorezm[a], g/l	Monotonically decreasing sigmoidal	7·0	7·0	7·0	Max value of corresponding layer	3	3 × 0·08
Groundwater salinity in SKKP[b], g/l							2 × 0·09
Slope in Khorezm, %	Monotonically decreasing linear	0·0	10·0	10·0	10·0	1	0·03
Slope in SKKP, %		0·0	27·78	27·78	27·78		

[a]Separate criterion maps representing seasonal (spring, summer, and autumn) fluctuations in groundwater table and groundwater salinity were prepared for land suitability assessment.
[b]For SKKP, available criteria included groundwater salinity in the spring and summer.

(suitability score = 1) in contrast to the areas with the lowest density of the canals (suitability score = 0; Table II, Figure 2).

In addition, the criteria "proximity to drains" and "density of drains" were included in the analysis. Operation of the drainage network is important for controlling the salt balance in the irrigated areas (Ibrakhimov *et al*., 2011). In the study region, freshwater availability is frequently insufficient for irrigation (Glantz, 1999), prompting the farmers in some districts to irrigate with a drainage water in water-scarce years. Rescaling of these criteria was performed similarly to that of the criteria related to irrigation canals.

Groundwater table

As is the case everywhere, GWT depth and groundwater salinity (GWS) influence tree growth in the irrigated cropland of the study area. If irrigation input is low, tree establishment is particularly influenced by the presence of shallow GWT with salt concentrations below the salinity tolerance of saplings (Schachtsiek *et al*., 2014). A shallow GWT generally is present within irrigated lowland areas; the GWT can be deeper within those sites where cropping and irrigation have been abandoned for extended periods (Ibrakhimov *et al*., 2011). In afforestation trials in the study region, tree plantations were established on marginal or abandoned cropping sites with wide ranges of GWT depths (0·4–2·0 m). In these tests, *E. angustifolia* showed at least 90% survival rate because of effective uptake of saline groundwater and with the support of deficit irrigation in the first years of growth (Table I). Kang *et al*. (2004) identified an optimal GWT range of 1·5–3·0 m for cultivation of *E. angustifolia*'s in arid China (Table I). Although a very shallow GWT (<0·5 m) is favored during the seedling phase when tree roots are not completely developed, a GWT this close to the surface would restrict longer term root growth (Ruger *et al*., 2005). Those sites characterized by a GWT deeper than 3 m would require higher irrigation inputs for establishing tree plantations. In nonirrigated drylands with a GWT in the range of 3·0–5·0 m and deeper, *E. angustifolia* did not grow well because of lack of the GWT contribution to overall soil moisture levels (Kang *et al*., 2004).

The relationship between GWT condition and tree plantation suitability can best be depicted using a symmetric sigmoidal curve, and such a curve was used to rescale the GWT layer into a continuous variable (Table II, Figure 2). The suitability increases monotonically from 0·5 to 1·5 m, does not change for the GWT range of 1·5–3·0 m, and decreases monotonically with GWT depths greater than 3·0 m.

Groundwater salinity

E. angustifolia is known as a relatively salt-tolerant species. Its actual salinity tolerance, however, also depends on soil moisture and nutrient conditions, on the ionic composition of the soil solution, and on the plant age (Kozlowski, 1997). In the study region, successful establishment of *E. angustifolia* saplings was reported for GWS ranging during the crop growing season from 0·6 to 5·4 g/l (Table I); such salinity levels are typically described as in the "slight to moderate" range (Rhoades *et al*., 1992).

There is an absence of experimental data on the field performance of *E. angustifolia* under conditions of GWS > 5·0 g/l within the study regions. As slight to moderate GWS levels are typical in Khorezm and SKKP, the optimal GWS level was assumed <7·0 g/l, according to the general classification described by Rhoades *et al.* (1992). Site suitability was assumed to decrease exponentially with a further increase in GWS. Such a relationship is best described by a monotonically decreasing sigmoidal curve (Table II, Figure 2). With this function, the first control point is the GWS value at which a location is considered to be unsuitable for afforestation (<7·0 g/l). Suitability rises sharply above the zero value with decreasing GWS levels, and the second control point is the value at which suitability approaches its maximum.

To capture within-season fluctuations of the groundwater parameters, three factors representing the GWT and GWS in the spring, summer, and fall were included in the analysis (Table II). Separate criterion maps representing GWT and GWS were prepared for land suitability assessment. Identical ranks and weights were assumed for each parameter.

Slope

Even small variations in microrelief (slopes < 10%) of the flat irrigated terrain in Khorezm influenced accumulation of topsoil salt in the fields, as well as the supply of irrigation water and its distribution within the field parcels. The slope was also included as a criterion, principally to delineate sites where costs for land leveling and salt leaching prior to plantation establishment would be minimized.

In order to characterize terrain differences, the suitability of a site for afforestation was assumed to decrease linearly with increasing slope. Thus, the slope criterion was rescaled using the monotonically decreasing linear function: Areas with a slope of 0% were considered as the most suitable for afforestation and areas with the steepest slope as the least suitable (Table II; Figure 2).

Evaluation of Land Suitability Model

An analysis was conducted to test the sensitivity of the results to changes in the assigned criteria weights. A suitability map based on the equal-weight WLC was computed and compared with an alternative suitability map generated from the WLC with criteria weights defined by experts. Chen and Paydar (2012) describe a procedure for validating these results utilizing a straightforward comparison procedure employing *in situ* crop distribution data. Such an assessment was not possible in this application, as afforestation is an innovative land use within the study region that is represented only by some experimental plantations.

RESULTS AND DISCUSSION

Suitability of Degraded Croplands for E. angustifolia

The multicriteria evaluation results in a continuous land suitability layer where a value of 0 indicates unsuitable and a value of 1 indicates most suitable sites. The overall suitability map was subsequently overlaid with the MODIS-based cropland degradation map (Dubovyk *et al*., 2013a) to highlight the suitability of *E. angustifolia* afforestation on cropping sites with declining productivity (Figure 3). The assessment revealed that the majority of the degraded irrigated cropland area was characterized by average and above-average suitability values. This is expected for the native species, which is broadly distributed in natural riparian habitat and within agroforestry systems in the study area.

The statistics describing the suitability values of the degraded cropland are shown in Table III. Overall, the suitability was higher for Khorezm compared with the SKKP; the highest suitability was observed in the Yangibazar district of Khorezm and the lowest suitability in the Turtkul district of the SKKP. Additionally, the range of suitability values was wider for the SKKP, suggesting higher spatial variability of the evaluation criteria in this area compared with Khorezm. In general, higher suitability values were observed in the districts bordering the Amudarya River, including Gurlan, Bagat, Khanka, and Khazarasp (Figure 1). This is likely the result of better access to irrigation water within these districts. In contrast, lower suitability was identified in the districts of Khiva, Kushkhupyr, and Turtkul that are in the more distant sections of the irrigation system.

Evaluation of Land Suitability Model

Tests of the model's sensitivity in relation to the selected criteria were conducted by assessing a series of reduced criteria suitability maps. These maps were calculated by sequentially omitting one criterion per calculation. The resultant maps were compared with the suitability map generated using the full criteria set. The results demonstrate clearly that removing the factor reflecting annual fluctuations in irrigation water supply had the most significant impact on the suitability results, the correlation between the maps decreasing to $R^2 = 0{\cdot}65$. Omitting the criteria of GWT depth also reduced the correlation between the maps (to $R^2 = 0{\cdot}85$). These results generally confirm the importance of the choice of criteria as well as the weighting factors assigned to each criterion for suitability assessment. In contrast, very little overall impact was observed when criteria related to irrigation and the drainage network were omitted (overall $R^2 = 0{\cdot}98$). Eliminating the criterion indicating proximity to irrigation canals had a somewhat greater impact, with a resultant $R^2 = 0{\cdot}90$. This implies that these criteria might be redundant for analyses at

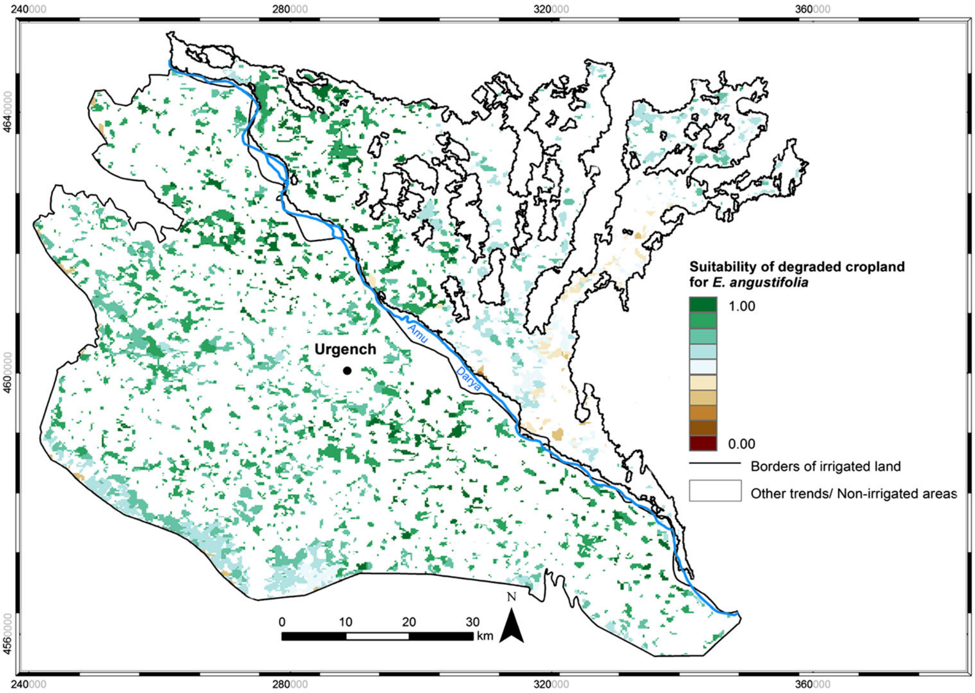

Figure 3. Suitability of degraded irrigated cropland in the lower Amudarya River basin for the establishment of *E. angustifolia* plantations.

a district scale but may be useful at finer spatial scales where higher resolution datasets could reveal impacts of these factors. Omitting the seasonal GWS criteria also made little difference in the results. Removing spring and summer criteria both produced an $R^2 = 0{\cdot}95$; omitting fall yielded $R^2 = 0{\cdot}99$. Omitting the slope criteria also had an insignificant impact ($R^2 = 0{\cdot}99$). These results can be explained by the overall low GWS within the irrigated areas (Ibrakhimov *et al.*, 2007) and a lack of significant topographic relief within the study area (Dubovyk *et al.*, 2013a).

Because of data limitations, our assessment did not include other relevant suitability criteria, such as soil characteristics.

Table III. Descriptive statistics of degraded cropland suitability for afforestation with *E. angustifolia*

	Land suitability			
District	Min	Max	Mean	Standard deviation
Bagat	0·62	0·88	0·78	0·05
Gurlen	0·66	0·85	0·78	0·03
Khanka	0·65	0·91	0·82	0·03
Khazarasp	0·59	0·87	0·76	0·05
Khiva	0·58	0·84	0·71	0·06
Kushkhupyr	0·56	0·79	0·72	0·04
Shavat	0·67	0·85	0·75	0·02
Urgench	0·63	0·85	0·71	0·02
Yangiaryk	0·50	0·83	0·66	0·07
Yangibazar	0·68	0·88	0·83	0·02
Khorezm	*0·50*	*0·91*	*0·76*	*0·06*
Beruniy	0·33	0·91	0·78	0·07
Ellikkala	0·26	0·83	0·61	0·04
Turtkul	0·18	0·74	0·53	0·10
Southern Karakalpakstan	0·18	0·91	0·65	0·13

The soil nitrogen content was not distinguished in the analysis because of the effective N_2-fixing ability of *E. angustifolia* (Khamzina *et al.*, 2009). This species also grows on a wide range of soil textures from sand to heavy clay (Tu, 2003). The absence of a soil texture criterion could be justified because the current assessment is focused on tree survival and establishment; *E. angustifolia* saplings' survival rates have been measured at $>90\%$ on sandy and silt-loamy soils, which are predominant in the study region (Khamzina, 2006; Khamzina *et al.*, 2008; Schachtsiek *et al.*, 2014). *E. angustifolia* has, however, shown significant variation in biomass production depending on soil texture (Khamzina *et al.*, 2006), and the soil texture parameter should be considered in further assessments when these data become available.

Spatially explicit data on soil salinity dynamics could be quite useful for the analysis of land suitability for afforestation in those areas where salinity is the main vegetation growth constraint. The contribution of saline GWT to soil salinity is significant when GWT levels exceed a threshold horizon above which groundwater rises via capillarity action toward the soil surface (Hillel, 2000). In our study region, this threshold was defined as 1·5–2·0 m, related to soil texture and GWS (Rakhimbaev *et al.*, 1992). In this case, then, we regard soil salinity as the product of GWT and GWS in combination with annual salt leaching and irrigation inputs. Groundwater and irrigation parameters then operated in place of explicit soil salinity data in the suitability model.

Our regional tests of the model's sensitivity to changes in the assigned criteria weights did not reveal substantially different results. The comparisons of the suitability map based on the equal weight WLC and the suitability map based on the WLC with expert-defined weights produced similar outputs: $R^2 = 0{\cdot}93$ for Khorezm and $R^2 = 0{\cdot}89$ for the SKKP.

The knowledge-based approach, commonly applied in land evaluation studies (Krueger *et al*., 2012), was also used here to assign weights and determine fuzzy membership functions. This approach is somewhat subjective compared with automated approaches (Liu *et al*., 2013). Implementation of the data-driven approach to model suitability is, however, before the availability of comprehensive quantitative information on environmental variables (Bradshaw *et al*., 2002). Further work might incorporate an empirical approach toward parameterization of the developed model. This approach would require incorporating data from an extended experimental dataset or from the simulated analyses of *E. angustifolia*'s survival and growth in response to prevailing environmental conditions in a specific area.

Implications for Afforestation Planning

Our assessment of the suitability of degraded croplands for afforestation with *E. angustifolia* revealed multiple small-scale patches (2–3 ha in size) scattered within the irrigated zone rather than contiguous large areas. This pattern should be considered in planning afforestation measures. The overall degraded cropland area suitable for the introduction of *E. angustifolia* (suitability values ≥ 0·5) totaled 75 287 ha (18% of the irrigated cropland area). The proportion of this area that eventually may be converted to tree plantations would depend on socioeconomic criteria and policy incentives. Degraded croplands associated with a high population density might be prioritized in afforestation planning as their rehabilitation would likely have more impact on the region's rural livelihood (Dubovyk *et al*., 2013a; Dubovyk *et al*., 2013b). Establishing tree plantations on the degraded margins of irrigated areas will require more intense management inputs. Afforestation decisions affecting these croplands should therefore be based on biophysical as well as economic assessments. Such a perspective can promote effective decisions regarding whether afforestation in a specific area is an ecologically viable alternative land use as well as whether the area is capable of generating additional income resources through the production of commercially viable commodities and services.

This suitability model has relatively modest minimum input data requirements and can be easily modified. Subject to data availability, it can be extended for suitability analysis of other tree species and/or ecosystem services by relevant planning authorities. Because data constraints and the absence of validation datasets, the assessment performed here can serve only for general planning purposes. Our results, however, serve to generalize and rescale the available site-specific information on the potential of agroforestry as an alternative land use in the degraded agricultural areas and can serve as the foundation for land rehabilitation planning in this region.

CONCLUSIONS

A GIS-based multicriteria regional evaluation model was developed for a landscape-scale suitability assessment of establishing plantations of *E. angustifolia* L. on degraded croplands. The results revealed higher than average suitability potential for afforestation in the lower Amudarya River basin and delineated specific sites most suitable for the potential introduction of trees. Parameters characterizing irrigation water supply and groundwater depth and salinity were most decisive in defining land suitability. These findings improve the understanding of spatial variations in the suitability of degraded irrigated cropland for *E. angustifolia* and subsequently support land rehabilitation planning through afforestation. This model can be further developed by integrating additional datasets relevant to suitability analyses of *E. angustifolia* as well as for other tree species that are important for biomass production and other ecological purposes.

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REFERENCES

Boroushaki S, Malczewski J. 2008. Implementing an extension of the analytical hierarchy process using ordered weighted averaging operators with fuzzy quantifiers in ArcGIS. *Computational Geosciences* **34**: 399–410.

Bradshaw CJA, Davis LS, Purvis M, Zhou Q, Benwell GL. 2002. Using artificial neural networks to model the suitability of coastline for breeding by New Zealand fur seals (Arctocephalus forsteri). *Ecological Modelling* **148**: 111–131.

Bruun TB, Elberling B, de Neergaard A, Magid J. in press. Organic carbon dynamics in different soil types after conversation of forest to agriculture. *Land Degradation & Development*: n/a-n/a. DOI: 10.1002/ldr.2205

Chen Y, Paydar Z. 2012. Evaluation of potential irrigation expansion using a spatial fuzzy multi-criteria decision framework. *Environmental Modelling & Software* **38**: 147–157.

Conrad C, Dech S, Dubovyk O, Fritsch S, Klein D, Löw F, Schorcht G, Zeidler J. 2014. Derivation of temporal windows for accurate crop discrimination in heterogeneous croplands of Uzbekistan using multitemporal RapidEye images. *Computers and Electronics in Agriculture* **103**: 63–74.

Djumaeva D, Lamers JPA, Khamzina A, Vlek PLG. 2013. The benefits of phosphorus fertilization of trees grown on salinized croplands in the lower reaches of Amu Darya, Uzbekistan. *Agroforestry Systems* **87**: 1–15.

Dubois D, Prade H. 1982. A class of fuzzy measures based on triangular norms. *International Journal of General Systems* **8**: 43–61.

Dubovyk O, Menz G, Conrad C, Lamers J, Lee A, Khamzina A. 2013a. Spatial targeting of land rehabilitation: a relational analysis of cropland productivity decline in arid Uzbekistan. *Erdkunde* **67**: 167–181.

Dubovyk O, Menz G, Conrad C, Thonfeld F, Khamzina A. 2013b. Object-based identification of vegetation cover decline in irrigated agro-ecosystems in Uzbekistan. *Quaternary International* **311**: 163–174.

Dubovyk O, Schachtsiek T, Khamzina A, Menz G. 2012. Exploring the biophysical potential of dryland afforestation on degraded lands in the downstream of the Amu Darya River, Uzbekistan. *Earth Bioresources and Life Quality* **1**: 1–14.

Fialho RC, Zinn YL. 2012. Changes in soil organic carbon under Eucalyptus plantations in Brazil: a comparative analysis. *Land Degradation & Development*: DOI: 10.1002/ldr.2158.

Glantz M. 1999. Creeping Environmental Problems and Sustainable Development in the Aral Sea Basin. Cambridge University Press: Cambridge.

Hbirkou C, Martius C, Khamzina A, Lamers JPA, Welp G, Amelung W. 2011. Reducing topsoil salinity and raising carbon stocks through afforestation in Khorezm, Uzbekistan. *Journal of Arid Environments* **75**: 146–155.

Hillel D. 2000. Salinity management for sustainable agriculture: integrating science, environment, and economics. Washington DC, World Bank.

Ibrakhimov M, Khamzina A, Forkutsa I, Paluasheva G, Lamers JPA, Tischbein B, Vlek PLG, Martius C. 2007. Groundwater table and salinity: Spatial and temporal distribution and influence on soil salinization in Khorezm region (Uzbekistan, Aral Sea Basin). *Irrigation and Drainage Systems* **21**: 219–236.

Ibrakhimov M, Martius C, Lamers JPA, Tischbein B. 2011. The dynamics of groundwater table and salinity over 17 years in Khorezm. *Agricultural Water Management* **101**: 52–61.

Jarnevich C, Reynolds L. 2011. Challenges of predicting the potential distribution of a slow-spreading invader: a habitat suitability map for an invasive riparian tree. *Biological Invasions* **13**: 153–163.

Kang S, Su X, Tong L, Shi P, Yang X, Abe Y, Du T, Shen Q, Zhang J. 2004. The impacts of human activities on the water–land environment of the Shiyang River basin, an arid region in northwest China. *Hydrological Sciences Journal* **49**: 410–427.

Katz GL, Shafroth PB. 2003. Biology, ecology and management of Elaeagnus angustifolia L. (Russian olive) in western North America. *Wetlands* **23**: 763–777.

Khamzina A. 2006. The assessment of tree species and irrigation techniques for afforestation of degraded agricultural landscapes in Khorezm, Uzbekistan, Aral Sea Basin. Göttingen Cuvillier Verlag.

Khamzina A, Lamers J, Worbes M, Botman E, Vlek P. 2006. Assessing the Potential of Trees for Afforestation of Degraded Landscapes in the Aral Sea Basin of Uzbekistan. *Agroforestry Systems* **66**: 129–141.

Khamzina A, Lamers JPA, Vlek PLG. 2008. Tree establishment under deficit irrigation on degraded agricultural land in the lower Amu Darya River region, Aral Sea Basin. *Forest Ecology and Management* **255**: 168–178.

Khamzina A, Lamers JPA, Vlek PLG. 2009. Nitrogen fixation by Elaeagnus angustifolia L. in the reclamation of degraded croplands of Central Asia. *Tree Physiology* **29**: 799–808.

König HJ, Zhen L, Helming K, Uthes S, Yang L, Cao X, Wiggering H. 2012. Assessing the impact of the sloping land conversation programme on rural sustainability in Guyuan, Western China. *Land Degradation & Development*. DOI: 10.1002/ldr.2164.

Kozlowski TT. 1997. Responses of woody plants to flooding and salinity. *Tree Physiology Monograph* **1**: 490–507.

Krueger T, Page T, Hubacek K, Smith L, Hiscock K. 2012. The role of expert opinion in environmental modelling. *Environmental Modelling & Software* **36**: 4–18.

Lamers JPA, Khamzina A, Worbes M. 2006. The analyses of physiological and morphological attributes of 10 tree species for early determination of their suitability to afforest degraded landscapes in the Aral Sea Basin of Uzbekistan. *Forest Ecology and Management* **221**: 249–259.

Liu Y, Jiao L, Liu Y, He J. 2013. A self-adapting fuzzy inference system for the evaluation of agricultural land. *Environmental Modelling & Software* **40**: 226–234.

Malczewski J. 2004. GIS-based land-use suitability analysis: A critical overview. *Progress in Planning* **62**: 3–65.

Pandey A, Chowdary VM, Mal BC, Dabral PP. 2011. Remote sensing and GIS for identification of suitable sites for soil and water conservation structures. *Land Degradation & Development* **22**: 359–372.

Paschke MW. 1997. Actinorhizal plants in rangelands of the western United States. *Journal Range Management* **50**: 62–72.

Rakhimbaev F, Bezpalov M, Khamidov M, Isabaev K, Alieva D. 1992. Peculiarities of crop irrigation in lower Amu Darya river areas. Tashkent, FAN.

Rhoades JD, Kandiah A, Mashali AM. 1992. The use of saline waters for crop production - FAO irrigation and drainage paper 48. Rome, FAO.

Rigueiro-Rodríguez A, Mosquera-Losada MR, Fernández-Núñez E. 2012. Afforestation of agricultural land with Pinus radiata D. don and Betula alba L. in NW Spain: Effects on soil PH, understorey production and floristic diversity eleven years after establishment. *Land Degradation & Development* **23**: 227–241. DOI: 10.1002/ldr.1072

Ruger N, Schluter M, Matthies M. 2005. A fuzzy habitat suitability index for Populus euphratica in the Northern Amudarya delta (Uzbekistan). *Ecological Modelling* **184**: 313–328.

Schachtsiek T, Lamers J, Khamzina A. 2014. Early Survival and Growth of Six Afforestation Species on Abandoned Cropping Sites in Irrigated Drylands of the Aral Sea Basin. *Arid Land Research and Management* **28**: 410–427.

Tu M. 2003. Element Stewardship Abstract for Phragmites australis. The Nature Conservancy: Arlington.

Tüshaus J, Dubovyk O, Khamzina A, Menz G. 2014. Comparison of Medium Spatial Resolution ENVISAT-MERIS and Terra-MODIS Time Series for Vegetation Decline Analysis: A Case Study in Central Asia. *Remote Sensing* **6**: 5238–5256.

Vasconcellos RLF, Bonfim JA, Baretta D, Cardoso EJBN. 2013. Arbuscular mycorrhizal fungi and glomalin-related soil protein as potential indicators of soil quality in a recuperation gradient of the atlantic forest in Brazil. *Land Degradation & Development*. DOI: 10.1002/ldr.2228.

Wu JP, Liu ZF, Sun YX, Zhou LX, Lin YB, Fu SL. 2013. Introduced Eucalyptus Urophylla plantations change the composition of the soil microbial community in subtropical China. *Land Degradation & Development* **24**: 400–406. DOI: 10.1002/ldr.2161.

Yager RR. 1988. On ordered weighted averaging aggregation operators in multicriteria decisionmaking. *IEEE Transactions on Systems, Man, and Cybernetics* **18**: 183–190.

Zadeh LA. 1965. Fuzzy sets. *Information and Control* **8**: 338–353.

